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www.ediuns.com.ar | ediuns@uns.edu.ar

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Preface

This volume includes the articles presented at the "Xth International Conference of Production Research-Americas" (ICPR-Americas 2020), held virtually from Bahía Blanca, Argentina from December 9 to 11, 2020. This conference was organized by the local organizing committee of the city of Bahía Blanca and was sponsored by the *International Foundation of Production Research* (IFPR). This conference aims at exchanging experiences and encouraging collaborative work among researchers and practitioners from the Americas and the Caribbean region.

The first ICPR Americas conference, took place in November 2002 in Saint Louis, Missouri, USA under the general theme of "Production Research and Computational Intelligence for Designing and Operating Complex Global Production Systems". This conference generated very positive responses from the attendees. From then on, the ICPR regional meeting was held at alternate years. The second version of the ICPR-Americas was held in August 2004 in Santiago, Chile with the conference theme "Information and Communication Technologies for Collaborative Operations Management". The third edition of the ICPR-Americas held in Curitiba, Brazil, had the general theme of "Rethinking Operation Systems: New Roles of Technology, Strategy and Organization in the America's Integration Era". This instance sought to promote a deep discussion about the role of Production Engineering in the America's integration process. In 2008, the venue of ICPR-Americas was Sao Paulo, Brazil at the Universidade de Sao Paulo Campus. The conference had the theme "The Role of Emerging Economies in the Future of Global Production: Creating New Multinationals". Bogota, Colombia hosted in 2010 the fifth conference with the subject "Technologies in Logistics and Manufacturing for Small and Medium Enterprises". The sixth edition (2012) was organized around the topic "Production Research in Americas Region: Agenda for the Next Decade" by the University of Santiago de Chile in Santiago. In Lima, Peru, the 2014 edition of ICPR-Americas addressed the general theme of "Towards Sustainable Eco-Industrialization through Applied Knowledge.". The eight edition was held at Valparaíso, Chile in 2016, and more recently, in 2018, the ninth conference was held at Bogotá, Colombia under the topic „Improving Supply Chain Management through Sustainability"

ICPR-Americas 2020 was the first edition carried out in virtual mode, due to the COVID-19 pandemic. Thanks to the participation and commitment of the attendees, the conference was carried out successfully, allowing many young researchers to participate in an international conference, in a year in which these opportunities were scarce. The ICPR-Americas meeting space gave them the opportunity to share their work, as well as exchange ideas and points of view, all in the cordial atmosphere that characterizes the ICPR-Americas conferences.

ICPR-Americas 2020 was organized by a local committee of the National University of the South, supported by the university and IFPR.

The conference received more than 280 papers, of which 245 were accepted and presented during the conference. The nationality of the authors was representative of the vast

majority of the countries of America, not only South America, but also Central and North America. Something that enriched the international experience that each of the participants took from the conference.

A couple of events associated with ICPR-Americas 2020 were also held: the “SIMPOSIO INDUSTRIAL” and the “SEMINARIO de ENSAYOS ESTUDIANTILES”. Both events allowed to broaden the scope and attendance of the conference. The accepted and presented works of both events are compiled within this volume.

Finally, it only remains for us to thank the National University of the South, especially the Departments of Engineering and Mathematics, as well as the General Secretariat of Science and Technology, for the support provided to carry out the event.

March 2021

Daniel Alejandro Rossit
Universidad Nacional del Sur and CONICET, Argentina

Fernando Tohmé
Universidad Nacional del Sur and CONICET, Argentina

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Simultaneous lot-sizing and scheduling with recovery options: problem formulation and analysis of the single-product case

Pedro Piñeyro[1][0000−0002−9155−7968] and Daniel Alejandro Rossit[2,3][0000−0002−2381−4352]

[1] Department of Operations Research, Institute of Computer Science, Faculty of Engineering, Universidad de la República, Julio Herrera y Reissig 565, CP 11300 Montevideo, Uruguay
ppineyro@fing.edu.uy,
[2] Department of Engineering, Universidad Nacional del Sur, Av. Alem 1253, Bahía Blanca 8000, Argentina
[3] INMABB-UNS-CONICET, Av. Alem 1253, Bahía Blanca 8000, Argentina
daniel.rossit@uns.edu.ar

Abstract. We address an extension of the discrete lot-sizing and scheduling problem in which the demand of products can be also satisfied by remanufacturing used products returned to the origin. A mixed-integer linear programming formulation is provided for the problem, assuming dynamic demand and returns values, and time-invariant costs of setup and holding inventory. We then present a numerical experimentation carried out with the mathematical model for the case of a single product, in order to evaluate the efficiency in both costs and solving times compared to the traditional problem without returns. From the results obtained we conclude that the problem with recovery options can lead to economic benefits only under certain assumptions on the costs and amounts of returns. In addition, according to the runtimes obtained for large instances of the problem, it seems to be much more difficult to solve than its traditional version without returns.

Keywords: lot-sizing, scheduling, remanufacturing, mathematical programming, optimization

1 Introduction

The discrete lot-sizing and scheduling problem (DLSP) refers to the problem of simultaneously determining the lots and sequence of production for a set of products, in order to meet the demand requirements on time, minimizing the sum of production and inventory holding costs. Unlike other lot-sizing problems, in the DLSP only one item can be produced at each period and the production process runs at full capacity, i.e., small bucket periods and all-or-nothing production policy are assumed. Therefore, the quantity of production in a period established as a positive production period is determined based on a certain production speed

expressed in units per period. In addition, setup costs are only incurred when there is product changeover, i.e., configuration costs of the production line are only incurred at the beginning of the production process of a product.

A mixed-integer linear programming (MILP) and a heuristic solving approach for the DLSP in the case of a single machine is proposed in [3]. In [4] the DLSP with sequence-dependent setup costs is formulated and analyzed. Salomon et al. in [17] present a classification scheme and complexity results for the DLSP. In particular, they demonstrated that the DLSP with stationary costs, positive setup costs and single machine is NP-hard. However, they note that the DLSP for a single product can be efficiently solved as in [8] and [24]. Several extensions and solving approaches have been proposed in the literature for the DLSP, such as [23] for costs with non-speculative motives and [7] for start-up times and backlogging in the context of a tire curing scheduling problem. More recently, the DLSP with sequence-dependent changeover costs and time is addressed in in [5]. Bi-objective formulations for the DLSP considering carbon emissions and renewable energy are presented in [10]. We refer the readers to [1] and [25] for recent surveys about the DLSP and extensions.

In recent years, the circular economy (CE) paradigm has emerged as an alternative to face the negative impact on the environment of the traditional linear model of producing, consuming and disposing [21]. As a recovery option, remanufacturing can be considered a critical component of the CE as it attempts to maintain the value of used products (also called cores or returns) and to reduce the use of raw material and energy [9], thus achieving a win-win-win situation for producers, consumes and environment. Remanufacturing is an industrial process in which it is warrantied that a used product is returned to its original condition or even better. It often involves inspection, sorting, disassembling, cleaning, testing, reprocessing and reassembling tasks. Remanufacturable products include automotive parts, electric home appliances, personal computers, cellular phones, cameras, vending machines, among others [11]. In the field of production planning, we can find the seminal works of [15], [16] and [26] that extend the traditional economic lot-sizing problem (ELSP) in order to include returns flow and remanufacturing process. Teunter et al. [22] introduce the economic lot-sizing problem with remanufacturing (ELSR) with either joint or separate setup scheme. They provide an efficient algorithm for the joint case and extend the Silver-Meal heuristic for the problem. In [12] consider the ELSR with disposal of returns and in [18] suggest several improvements for the extended Silver-Meal heuristic. In [2], [19], [13] are suggested and evaluated different solving procedures for the ELSR based on metaheuristic approaches, and [14] considers the ELSR with recovery targets. We refer to [21] for a recent survey about production planning with recovery options.

In this paper, we extend the DLSP in order to include the returns flow, and assuming that demand can be also satisfied by remanufacturing used products. We refer to this problem extension as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). We provide a MILP formulation for the problem and present and analyze the results of a numerical experimentation

carried out in order to evaluate the efficiency in both costs and solving time of this hybrid production-remanufacturing system in the case of a single product. As far as we know, this DLSP extension has not been considered in the literature before. However, we note that there are some works that combine scheduling and remanufacturing, but for different problem assumptions [27], [6], [20].

The remainder of this paper is organized as follows. In Section 2 we present the description and the MILP formulation suggested for the problem under consideration. Section 3 provides the results and the analysis of the numerical experimentation carried out in order to evaluate the efficiency of the DLSR for the case of a single product. Finally, in Section 4 we present the conclusions and some possible directions for future research.

2 Problem description and formulation

The problem tackled in this paper can be stated as follows. We address a dynamic hybrid production-remanufacturing system with a single machine for processing $J > 0$ products under all-or-nothing production policy and over a finite planning horizon $T > 0$. Small-bucket periods are assumed. Therefore, only one product can be produced or remanufactured, but not both in the same period. The production and remanufacturing speeds for each product j, p_j and r_j respectively, are expressed as unit per period. Demand for a product j in a period t must be satisfied on time (backlogging is not allowed) from produced or remanufactured products generated in the same period (zero lead-time is assumed) or in a previous period and held in the inventory of serviceable products. Demand and returns values are assumed known in advance for each product and period over the planning horizon. Production and remanufacturing setup costs are incurred when there is product changeover. There are also linear costs for carrying on one unit of serviceable or used product from one period to the next one. Setup and inventory holding costs are assumed known and time-invariant. The objective is to determine the lots and sequence of products to be produced and remanufactured in order to satisfy the demand requirements on time, minimizing the sum of the costs involved.

Below we present the notation used for the problem from here and throughout the rest of the paper.

Sets and indices:

J : Number of products, with index $j \in \{1, ..., J\}$.
T : Number of periods, with index $t \in \{0, 1, ..., T\}$.

Parameters:

D_{jt} : Demand of product j in period $t > 0$.
R_{jt} : Returns of product j available in period $t > 0$.
K_j^p : Production setup cost of product j.
K_j^r : Remanufacturing setup cost of product j.
h_j^s : Holding cost for serviceable product j per unit and per period.
h_j^u : Holding cost for used product j per unit and per period.
p_j : Production speed for product j (units per period).
r_j : Remanufacturing speed for product j (units per period).

Variables:

I_{jt}^s : Inventory of serviceable product j at the end of period t.
I_{jt}^u : Inventory of used product j at the end of period t.
y_{jt}^p : $y_{jt}^p = 1$ indicates that product j is produced in period t;
$y_{jt}^p = 0$, otherwise.
y_{jt}^r : $y_{jt}^r = 1$ indicates that used product j is remanufactured in period t;
$y_{jt}^r = 0$, otherwise.
z_{jt}^p : $z_{jt}^p = 1$ indicates a production setup for product j in period $t > 0$;
$z_{jt}^p = 0$, otherwise.
z_{jt}^r : $z_{jt}^r = 1$ indicates a remanufacturing setup for product j in period $t > 0$;
$z_{jt}^r = 0$, otherwise.

Based on the notation of above, the DLSR can be formulated as the following MILP. We note that it can be considered an extension of that introduced in [8] and [24] for the DLSP.

$$\min \quad \sum_{j=1}^{J}\sum_{t=1}^{T}(K_j^p z_{jt}^p + K_j^r z_{jt}^r + h_j^s I_{jt}^s + h_j^u I_{jt}^u) \tag{1}$$

$$\text{s.t.} \quad I_{jt}^s = I_{j(t-1)}^s + p_j y_{jt}^p + r_j y_{jt}^r - D_{jt}, \quad \forall j, t > 0 \tag{2}$$

$$I_{jt}^u = I_{j(t-1)}^u + R_{jt} - r_j y_{jt}^r, \quad \forall j, t > 0 \tag{3}$$

$$\sum_{j=1}^{J}(y_{jt}^p + y_{jt}^r) \leq 1, \quad \forall t > 0 \tag{4}$$

$$z_{jt}^p = y_{jt}^p - y_{j(t-1)}^p, \quad \forall j, t > 0 \tag{5}$$

$$z_{jt}^r = y_{jt}^r - y_{j(t-1)}^r, \quad \forall j, t > 0 \tag{6}$$

$$I_{j0}^s = I_{j0}^u = y_{j0}^p = y_{j0}^r = 0, \quad \forall j \tag{7}$$

$$I_{jt}^s, I_{jt}^u \geq 0, \quad \forall j, t \tag{8}$$

$$y_{jt}^p, y_{jt}^r, z_{jt}^p, z_{jt}^r \in \{0, 1\}, \quad \forall j, t \tag{9}$$

The objective function (1) minimizes the sum of setup and inventory holding costs. Constraints (2) and (3) are the inventory balance equations for serviceable and used products, respectively. Constraints (4) establish that: i) only one product can be produced or remanufactured in certain period; ii) production and remanufacturing can not be carried out in the same period. Constraints (5) and (6) are for establishing the production and remanufacturing setup cost incurred when there is product changeover, respectively. The constraints (7) mean that the initial inventory level for all products is assumed zero and that the system is initially idle. Finally, (8) and (9) are the domain constraints for the decision variables.

3 Numerical experimentation

In this section we provide the results and the analysis of the numerical experiments carried out to evaluate the mathematical model suggested for the DLSR. Specifically, we are interested in compare the efficiency in both costs and solving time for the problem with and without returns, i.e, the DLSR and the DLSP. We note that the MILP of Section 2 in which the parameters, variables and specific constraints related to returns are removed, corresponds to the formulation of the DLSP.

To facilitate the understanding of the results and to make a more effective comparison, we consider for the experiments the case of a single product ($j = 1$).

3.1 Experiments design

The instances were generated based on the benchmark set introduced in [22] and [18] for the ELSR, also used in [2], [19], [13] and [14]. All them have a

planning horizon T of 22 periods (workdays of a month). Demand values D_{1t} were generated according to a normal distribution with mean 100 and 20% of coefficient variation. Returns R_{1t} were also generated using a normal distribution with means 50, 70 and 100, and 20% of coefficient variation. The setup cost of production K_1^p is set to 2000 and the setup cost of remanufacturing K_1^r can be 200, 500 and 2000. The unit cost for holding inventory of serviceable products h_1^s is set to 1 and for used products h_1^u can be 0.2, 0.5 and 0.8. Production speed p_1 is set to 200 units per period, and the remanufacturing speed r_1 can take values on 200, 300 and 400 units per period. Note that, as is to be expected in practice, it is assumed that remanufacturing costs are at most equal to production costs and that remanufacturing speed is at least equal to production speed. We generate 10 instances for each on of the 3^4 configurations, that is 810 instances in total. In addition, to evaluate the solving time, we generate one instance for each configuration, with planning horizons of 22, 44, 66, 88, 110 and 132 periods, that is $81 \times 6 = 486$ instances in total.

The model was coded in AMPL and solved for all the instances of above with CPLEX 12.9.0.0 with a time limit of 1800 seconds, on a PC with 8 CPUs Intel Core i7-6700 3.40GHz, 64-bit, 24GB of RAM and CentOS Linux 7.

3.2 Analysis of results for instances with $T = 22$

Next, we present and analyze the results obtained for the instances with a planning horizon of $T = 22$ periods. The values shown in Table 1 are the average cost, the standard deviation and maximum cost of the optimal solutions obtained with CPLEX for the DLSR and DLSP. We decided not to report the runtimes, since they were very low for both problems, less than half a second for all the 810 instances. In the first row of the table, labeled as *"All instances"*, we show the average cost considering all the instances, which is 12480.1 for the DLSR and 10828.9 for the DLSP. This represents around of 15% increase in the costs for the DLSR in average. However, we can note that in the cases of low-cost returns ($K_1^r = 200$ or $h_1^u = 0.2$), the costs are in average a little more favorable for the DLSR. The average costs of these cases are highlighted in the table (underlined and in bold). In fact, for each one of the 90 instances with $K_1^r = 200$ and $h_1^u = 0.2$, we want to remark that the cost of the DLSR optimal solutions is lower than the cost of the DLSP optimal solutions, even reaching differences of more than 35% in favor of the DLSR. We also note that the total number of instances for which the cost is favorable for the DLSR is 255, that is 30% of the total instances. On the other hand, we note that the maximum gap between the average costs of the DLSR and DLSP is for the cases of high-cost returns ($K_1^r = 2000$ and/or $h_1^u = 0.8$).

In the cases of variations on the average quantity of returns (R_{1t}), we note that they do not have a significant impact on the cost gaps. However, we note a favorable trend to the DLSR as the amount of returns increase, as it can be noted for the case of large returns ($R_{1t} = 100$). The opposite behaviour can be observed for the remanufacturing speed (three last rows of Table 1): as the remanufacturing speed increases, also do the average cost gap between DLSR and

DLSP. Therefore, it would be more economically convenient to consider similar speeds for production and remanufacturing, although in fact the remanufacturing speed could be higher, as it often requires less labor effort, materials, and energy.

In Table 1, the higher standard deviation and maximum values obtained for the DLSR compared to the DLSP, may be due to the fact that the variations are in the parameters related to the returns, which do not affect the DLSP. However, this appreciable dispersion in the costs of the DLSR optimal solutions observed for all the instances, would show that the variation in the parameter values has a significant impact on the efficient resolution of the problem.

Table 1. Summary of results for the 810 instances with $T = 22$ for DLSR and DLSP. The columns represent the average, standard deviation and maximum value of the optimal solutions obtained with CPLEX.

		Average		***Stand. desv.***		***Maximum***	
		DLSR	**DLSP**	**DLSR**	**DLSP**	**DLSR**	**DLSP**
All instances		12480.1	10828.9	2858.7	413.6	21086.2	12065.0
R_{1t}	**50**	12653.5	10837.5	2206.8	402.9	18098.0	12065.0
	70	12625.5	10841.8	2671.6	438.0	19351.6	11930.0
	100	12161.3	10807.3	3523.8	399.4	21086.2	12007.0
K_1^r	**200**	**10447.5**	**10834.4**	1890.4	407.0	14865.8	12065.0
	500	11553.2	10816.9	1712.9	413.3	15839.8	11868.0
	2000	15439.6	10835.3	2066.4	421.6	21086.2	12007.0
h_1^u	**0.2**	**10600.6**	**10804.5**	2116.3	393.0	15177.6	11794.0
	0.5	12582.6	10850.2	2483.1	442.9	17746.0	12065.0
	0.8	14257.1	10831.9	2684.7	403.4	21086.2	11930.0
r_1	**200**	11519.7	10846.1	2672.3	419.6	17711.6	12065.0
	300	12610.2	10819.1	2825.5	433.9	20403.2	12007.0
	400	13310.3	10821.5	2796.2	386.9	21086.2	11930.0

The cases in which the DLSR obtained lower costs than DLSP, that is, $K_1^r = 200$ and $h_1^u = 0.2$, are presented in more detail in Tables 2 and 3, respectively.

Table 2 shows the average cost of the optimal solutions for the DLSR and DLSP for the instances with $K_1^r = 200$. The rest of the parameters (R_{1t}, h_1^u and r_1) vary as described in Section 3.1. In column "Gap" we report the difference in percentage between the average costs of the optimal solutions determined as: $100 \times (DLSR\_cost - DLSP\_cost)/DLSP\_cost$). From Table 2 we first note that the DLSR average costs are lower than DLSP in most cases (negative values in the Gap column). In terms of R_{1t}, it can be seen that as the value of returns increases, the cost of the DLSR optimal solutions decreases, reaching a percentage gap near to -14%. For the cases of h_1^u, we note that the sensitivity of the DLSR is significant with respect to this parameter, since the cost gaps vary from -19.3% ($h_1^u = 0.2$) to 11.3% ($h_1^u = 0.8$). Regarding the remanufacturing speed r_1, the analysis is similar to the cases of h_1^u: the cost of the DLSR is very sensitive and increases as the value of r_1 increases, as we mentioned at the beginning of this subsection for the analysis of the results presented in Table 1. In addition,

Table 2. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $K_1^r = 200$.

			DLSR	DLSP	Gap
$K_1^r = 200$	R_{1t}	**50**	11217.9	10789.1	4.0%
		70	10778.4	10877.5	-0.9%
		100	9346.2	10836.6	-13.8%
	h_1^u	**0.2**	8736.0	10831.8	-19.3%
		0.5	10520.5	10816.1	-2.7%
		0.8	12086.0	10855.3	11.3%
	r_1	**200**	9415.7	10881.8	-13.5%
		300	10527.7	10810.3	-2.6%
		400	11399.1	10811.1	5.4%

we observe that the costs are significantly favorable for the DLSR in the case in which the production and remanufacturing speed are the same ($p_1 = r_1 = 200$).

Table 3. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $h_1^u = 0.2$.

			DLSR	DLSP	Gap
$h_1^u = 0.2$	R_{1t}	**50**	10938.7	10812.1	1.2%
		70	10636.5	10856.8	-2.0%
		100	10226.5	10744.7	-4.8%
	K_1^r	**200**	8736.0	10831.8	-19.3%
		500	9862.4	10808.2	-8.8%
		2000	13203.3	10773.7	22.6%
	r_1	**200**	9881.1	10833.5	-8.8%
		300	10740.5	10801.3	-0.6%
		400	11180.1	10778.9	3.7%

Table 3 shows the results for the instances with $h_1^u = 0.2$. The meaning of the columns is the same as in Table 2. From Table 3 we can note that there are more instances in which the costs of the DLSR is lower than the costs of the DLSP (negative values in column "Gap"). The effect observed for the returns cases R_{1t} is similar to that seen in Table 2, but less marked: as returns amounts increase, the cost of the DLSR decreases. A high sensitivity for the costs of the DLSR optimal solutions is observed against different values of K_1^r, with a percentage gap from -19.3% for $K_1^r = 200$ to 22.6% for $K_1^r = 2000$. For the cases of the remanufacturing speed (r_1), the results are also similar for that observed in Table 2, but, once again, not so marked.

3.3 Analysis of results for large instances

We present in this subsection the results of the experiments carried out to evaluate the computational effort required to solve the problems DLSR and DLSP.

In Table 4 we present the runtimes in seconds for each problem, along with the number of times that the time limit of 1800 seconds, established to CPLEX, is attained. In Figure 1 we show the CPU times required by CPLEX for solving the problems for the different values of T under consideration, represented on a logarithmic scale. As it can be seen in Table 4 and Figure 1, DLSR is considerably more computationally expensive than DLSP. While the CPU times for the DLSP are around 1 second (even for the larger case of $T = 132$), in the case of the DLSR, they grow suddenly (more than 500 seconds for $T = 132$). This is evidenced by the number of times that the time limit of execution is reached by CPLEX for the DLSR, which begins to increase in larger instances. On the other hand, for the DLSP the time limit is never attained.

Table 4. Average runtimes (in seconds) and number of times that the execution time limit is reached by CPLEX to solve the problems DLSR and DLSP for the different values of T considered.

	DLSR		**DLSP**	
T	**Runtime**	**#Tim.lim.**	**Runtime**	**#Tim.lim.**
22	0.07	0	0.006	0
44	0.53	0	0.10	0
66	9.02	0	0.26	0
88	134.03	4	0.82	0
110	362.44	13	1.11	0
132	513.67	19	1.34	0

Finally, we note that the cost gaps for the large instances show, on average, the same behaviour as that observed for the 810 instances with $T = 22$ periods, that is, around a 15% increase for the DLSR compared to the DLSP.

4 Conclusions

In this paper we have tackled an extension of the discrete lot-sizing and scheduling problem in which the demand requirements of products can be also satisfied by remanufacturing used products returned to the origin. We refer to this problem as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). Remanufacturing can be considered as a key element of the Circular Economy, a paradigm that has emerged to counteract the negative effect on the environment of the traditional linear production of produce, use and dispose.

We provide a MILP formulation for the problem and analyze the results of a numerical experimentation carried out for the case of a single product, with the aim to compare the efficiency in both costs and solving time of the DLSR against the DLSP (the traditional problem without returns). From the numerical experiments conducted, we conclude that the problem extension with recovery options can offer economic benefits in the case of low-cost returns and, to a lesser extent, for those cases in which the number of returns is relatively high compared

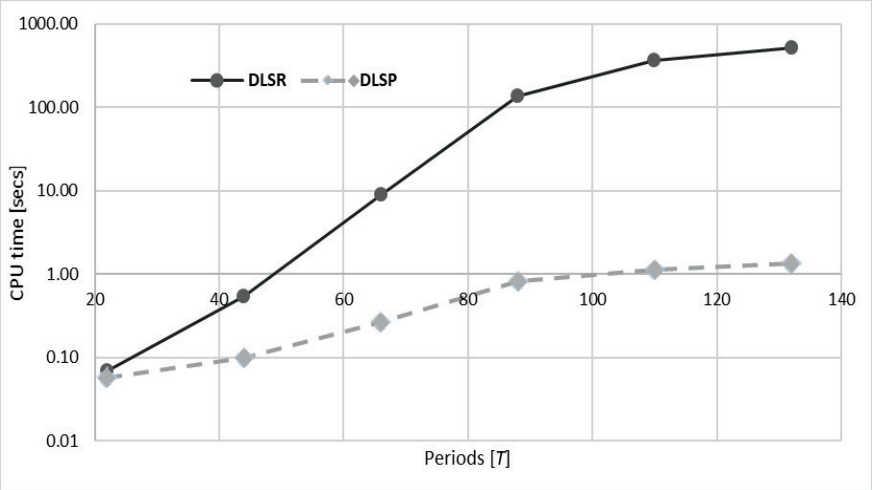

Fig. 1. CPU times in average required by CPLEX to solve the problems DLSR and DLSP for the different values of T. The CPU time is expressed in logarithmic scale in seconds.

to the demand requirements. In addition, we note that similar production and remanufacturing speeds appear to be a more favorable configuration, even in those cases with large returns. In terms of solving times, we show that the DLSR is much harder to solve than the DLSP, in particular, as the size of the instances increases. Thus, we conjecture that the DLSR belongs to the complexity class of NP-hard problems.

Taking into account the results of the numerical experimentation summarized above, future research on DLSR should involve the development of efficient and effective solving procedures for the problem, possibly extending those suggested for the DLSP or ELSR. Another interesting topic to address is the analysis of the order of complexity of the problem. This analysis should involve not only the general case, but also particular cases such as the case of a single product as in [24] for the DLSP, or the case of sufficient returns at the first period as in [15] and [16] for ELSR. It would be also interesting to study the DLSR with more than one machine or processing line. In particular, the case in which production and remanufacturing are allowed in the same period. Considering the environmental side of the problem, it would be interesting to investigate the returns usage rate in the optimal or high quality solutions. Also including more realistic assumptions, such as the non-uniform condition of the returns (heterogeneous quality), may be an interesting extension to consider for the problem tackled here.

References

1. Copil, K., Wörbelauer, M., Meyr, H., Tempelmeier, H.: Simultaneous lotsizing and scheduling problems: a classification and review of models. OR spectrum **39**(1), 1

– 64 (2017)
2. Fazle Baki, M., Chaouch, B.A., Abdul-Kader, W.: A heuristic solution procedure for the dynamic lot sizing problem with remanufacturing and product recovery. Computers & Operations Research **43**, 225 – 236 (2014)
3. Fleischmann, B.: The discrete lot-sizing and scheduling problem. European Journal of Operational Research **44**(3), 337 – 348 (1990)
4. Fleischmann, B.: The discrete lot-sizing and scheduling problem with sequence-dependent setup costs. European Journal of Operational Research **75**(2), 395 – 404 (1994)
5. Gicquel, C., Lisser, A., Minoux, M.: An evaluation of semidefinite programming based approaches for discrete lot-sizing problems. European Journal of Operational Research **237**(2), 498 – 507 (2014)
6. Giglio, D., Paolucci, M., Roshani, A.: Integrated lot sizing and energy-efficient job shop scheduling problem in manufacturing/remanufacturing systems. Journal of Cleaner Production **148**, 624 – 641 (2017)
7. Jans, R., Degraeve, Z.: An industrial extension of the discrete lot-sizing and scheduling problem. IIE Transactions **36**(1), 47 – 58 (2004)
8. Kuik, R., Salomon, M., Van Hoesel, S., Van Wassenhove, L.N.: The single item discrete lotsizing and scheduling problem: Linear description and optimization. Tech. rep., Erasmus University (10 1989)
9. Kurilova-Palisaitiene, J., Sundin, E., Poksinska, B.: Remanufacturing challenges and possible lean improvements. Journal of Cleaner Production **172**, 3225 – 3236 (2018)
10. Liu, C.H.: Discrete lot-sizing and scheduling problems considering renewable energy and CO2 emissions. Production Engineering **10**(6), 607 – 614 (2016)
11. Matsumoto, M., Umeda, Y.: An analysis of remanufacturing practices in Japan. Journal of Remanufacturing **1**(1), 2 (2011)
12. Piñeyro, P., Viera, O.: Inventory policies for the economic lot-sizing problem with remanufacturing and final disposal options. Journal of Industrial & Management Optimization **5**(2), 217 – 238 (2009)
13. Piñeyro, P., Viera, O.: The economic lot-sizing problem with remanufacturing: analysis and an improved algorithm. Journal of Remanufacturing **5**(1), 1 – 13 (2015)
14. Piñeyro, P., Viera, O.: Heuristic procedure for the economic lot-sizing problem with remanufacturing and recovery targets. Journal of Remanufacturing **8**(1), 39 – 50 (2018)
15. Richter, K., Sombrutzki, M.: Remanufacturing planning for the reverse Wagner/Whitin models. European Journal of Operational Research **121**(2), 304 – 315 (2000)
16. Richter, K., Weber, J.: The reverse Wagner/Whitin model with variable manufacturing and remanufacturing cost. International Journal of Production Economics **71**(1), 447 – 456 (2001)
17. Salomon, M., Kroon, L.G., Kuik, R., Van Wassenhove, L.N.: Some extensions of the discrete lotsizing and scheduling problem. Managment Science **37**(7), 801 – 812 (1991)
18. Schulz, T.: A new silver–meal based heuristic for the single-item dynamic lot sizing problem with returns and remanufacturing. International Journal of Production Research **49**(9), 2519 – 2533 (2011)
19. Sifaleras, A., Konstantaras, I., Mladenović, N.: Variable neighborhood search for the economic lot sizing problem with product returns and recovery. International Journal of Production Economics **160**, 133 – 143 (2015)

20. Sun, H., Chen, W., Liu, B., Chen, X.: Economic lot scheduling problem in a remanufacturing system with returns at different quality grades. Journal of Cleaner Production **170**, 559 – 569 (2018)
21. Suzanne, E., Absi, N., Borodin, V.: Towards circular economy in production planning: Challenges and opportunities. European Journal of Operational Research **287**(1), 168 – 190 (2020)
22. Teunter, R.H., Bayindir, Z.P., Den Heuvel, W.V.: Dynamic lot sizing with product returns and remanufacturing. International Journal of Production Research **44**(20), 4377 – 4400 (2006)
23. Van Eijl, C., Van Hoesel, C.: On the discrete lot-sizing and scheduling problem with wagner-whitin costs. Operations Research Letters **20**(1), 7 – 13 (1997)
24. Van Hoesel, S., Kuik, R., Salomon, M., Van Wassenhove, L.N.: The single-item discrete lotsizing and scheduling problem: optimization by linear and dynamic programming. Discrete Applied Mathematics **48**(3), 289 – 303 (1994)
25. Wörbelauer, M., Meyr, H., Almada-Lobo, B.: Simultaneous lotsizing and scheduling considering secondary resources: a general model, literature review and classification. OR Spectrum **41**(1), 1436 – 6304 (2019)
26. Yang, J., Golany, B., Yu, G.: A concave-cost production planning problem with remanufacturing options. Naval Research Logistics **52**(5), 443 – 458 (2005)
27. Zanoni, S., Segerstedt, A., Tang, O., Mazzoldi, L.: Multi-product economic lot scheduling problem with manufacturing and remanufacturing using a basic period policy. Computers & Industrial Engineering **62**(4), 1025 – 1033 (2012)